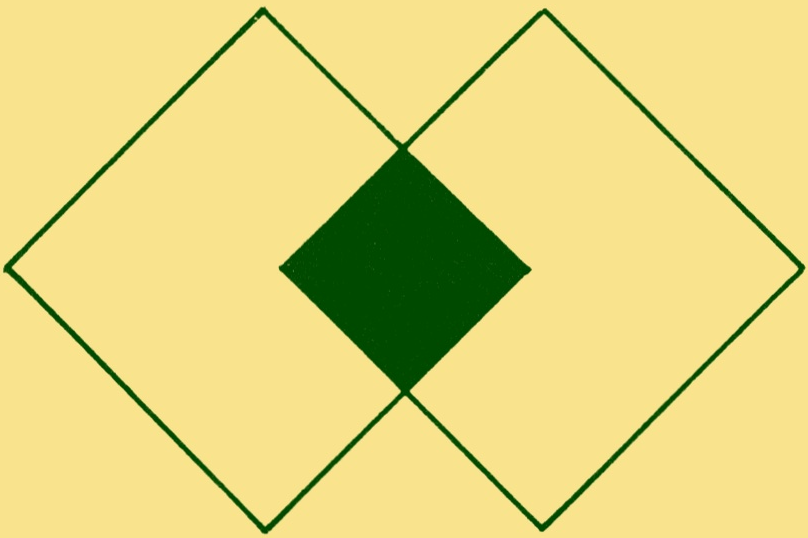
THINGS of science



POLARIZED LIGHT

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POLARIZED LIGHT

Light consists of many waves moving through space. Each of these waves vibrates in a sidewise or transverse direction, perpendicular to the direction in which the wave is traveling. In ordinary light, vibrations take place in all possible transverse directions (Fig. 1).

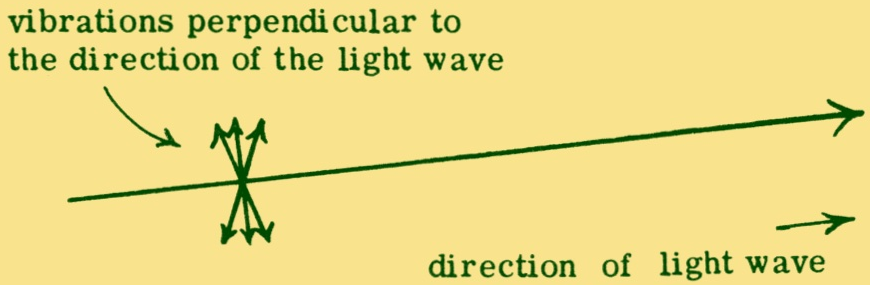


Fig. 1

These transverse vibrations may be in any direction at right angles to the direction of light propagation. Light rays from an automobile headlight, for example, travel forward, but the light's vibrations are at right angles to the forward motion.

Experiment 1. To help visualize this, take the wire in your unit and make a small model light wave by bending the wire, as illustrated in Figure 2, into a series of equal size "waves" about ½-inch deep. The vibrations of the light ray, represented by the curves, are at right angles to the path of the light wave, indicated by the straight sections of the wire at the ends.

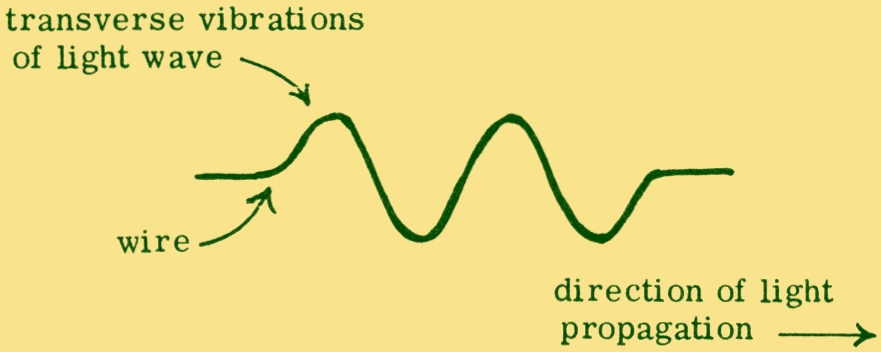


Fig. 2

Under certain conditions, vibrations of a beam of light may all be in a single plane. The light then is said to be linearly polarized.

With the materials in this unit, you will demonstrate how light can be polarized and study some of the characteristics of polarized light.

First identify and examine the specimens in your unit.

LINEAR POLARIZING FILTERS—Two one-inch square pieces of film; grayish in color.

QUARTER-WAVE RETARDATION FILM—Clear plastic; one-inch square.

MODEL "POLARIZING FILTERS"—Two pieces of heavy paper with alternating bars and open spaces.

MICA—Sheet of brownish gray mineral; irregular in shape.

CRYSTALLINE BENZOIC ACID—Fine white crystals in polyethylene bag.

CELLOPHANE—Clear film; 3 x 5 inches in size.

FINE WIRE—About 4½ inches long.

THE POLARIZER

Until about 40 years ago, there was no economical means of producing linearly polarized light. Crystals such as calcite or tourmaline could be used, but they were small, expensive and seldom seen outside of laboratories.

In 1932, Dr. Edwin H. Land, president and director of research of Polaroid Corporation, then 23, solved the problem. He discovered an economical method of mass-producing large sheets of polarizer. Besides filtering polarized light with great efficiency, these sheets can be easily cut into pieces of any desired size and shape.

Sheet polarizers, like the specimens in your unit, are capable, not only of polarizing light, but also of controlling light already polarized. Thus, it has found widespread use in reducing glare and light intensity. Sunglasses, filters for cameras and polarized film placed over ship-bridge windows are just a few examples of its use.

How does a linear polarizer work? What does it consist of?

Your Polaroid film is made of polyvinyl alcohol, a plastic synthetic material contain-

ing long-chain molecules which ordinarily twist, coil and kink in all directions. When the sheet of polyvinyl alcohol is heated, stretched and cooled, these long molecules align themselves in parallel chains. The plastic becomes oriented by the process.

Iodine is next added to the plastic, and the long, thin iodine molecules align themselves between the parallel molecules of polyvinyl alcohol.

The combination of the iodine and polyvinyl alcohol produces the polarizing material that transmits light vibrating only in the direction of the alignment, effectively blocking light vibrating in all other planes.

If the molecules in the sheet were scattered in all directions, they would accomplish no useful function. But they are not arranged randomly; all of them are aligned in the same direction like the pickets in a fence. Being parallel to one another, they work in unison, transmitting light of one plane only.

(In some of Dr. Land's earlier polarizers, millions of tiny crystals were used instead of molecules and with a high powered microscope, the individual crystals could be seen, lined up parallel to each other.)

Experiment 2. To demonstrate how the polarizer works, take your wire model "ray of light" (Fig. 2). Be sure all the

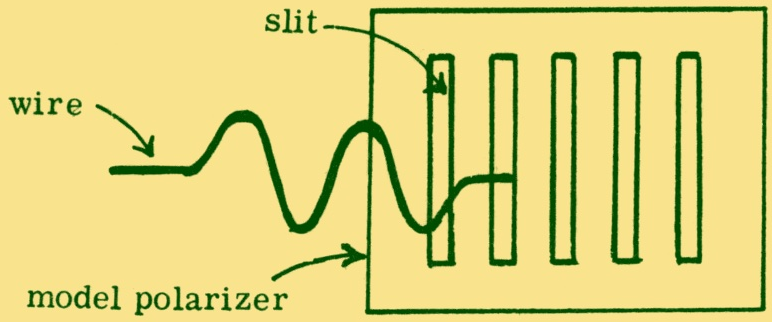


Fig. 3

waves are in the same plane so that your model will represent linearly polarized light.

Hold one end of your "light ray" and move it forward in any direction at any angle. As long as there is nothing in front of the model, you can direct it toward any point you wish. Ordinary light is made up of many such waves vibrating in various transverse planes as they travel through the air.

Now place one of your model polarizers in front of the wire light ray. The model polarizer represents the parallel alignment of the molecules in a Polaroid film and the spaces between them through which light can pass. Can you make the model ray pass through the slits in the model (Fig. 3)?

You will find that the ray will pass through any of the slits as long as the transverse waves are in the same direction as the length of the slit. When its vibra-

tions or waves are at an angle to the slits, or in a different plane, its passage is blocked.

Just as demonstrated in the experiment with the models, only light rays that are in the same plane as the alignment of the molecules can pass through a polarizing film. Light emerging from a polarizer, therefore, will all be in the same plane and linearly polarized (or plane polarized).

EFFECT WITH TWO POLARIZERS

Experiment 3. Prop one of the cardboard model polarizers on a table and place the other model about one inch in front of it with its slits parallel to the slits of the other model and directly opposite each other. Now pass your wire light ray through the first model polarizer and on through the second. The polarized light emerging from the first model passes readily through the second model whose "molecules" are parallel to those of the first model.

Turn the rear model polarizer so that its slits are at right angles to those of the model polarizer in front. Try to pass the model light ray through both model polarizers. Do you succeed? No, because the criss-crossing slits deny passage of the ray.

Experiment 4. Now look through

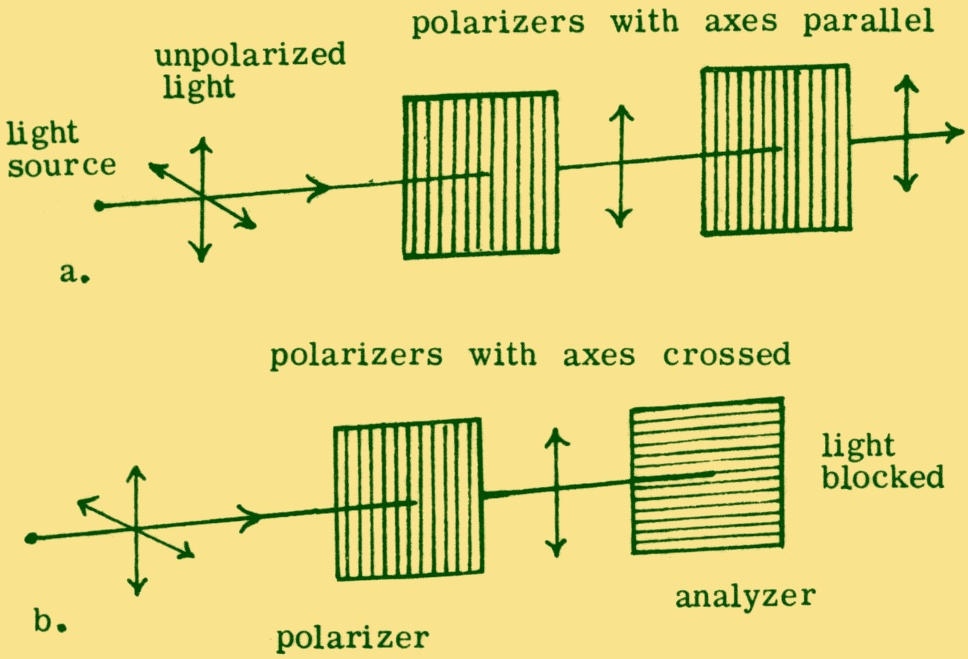


Fig. 4

one of your real Polaroid films. Can you see through it? Turn it around at different angles. You can see through it no matter in which direction it is rotated.

Ordinary light is composed of light rays vibrating in every direction and so some of it will pass through a polarizer regardless of the axis. However, the light reaching your eyes after passing through the filter is linearly polarized.

Experiment 5. Hold your two polarizers about an inch apart, one directly in front of the other, with their axes parallel. When the axes are parallel, the maximum amount of light will pass through the two filters. Look through them at a lighted

lamp.

Now give the Polaroid film nearer you a quarter turn (90°) so that the axes are at right angles to each other. What happens? The light is practically blacked out. The reason for this is obvious from your results with the models (Fig. 4, a and b). When two polarizers are used together in this manner, the first is called the polarizer and the second the analyzer (Fig. 4b).

The light from the lamp transmitted through the first filter (the polarizer) all vibrate in the same plane. When the axis of the second filter (the analyzer) is at right angles to the transverse waves of the polarized light striking it, no light waves reach your eyes and everything appears black.

For easier handling, make holders for your two Polaroid films. Cut two strips of thin cardboard about 2 x 4 inches in size. About one-half inch from one end cut out a square about one-sixteenth of an inch smaller than the Polaroid. Place the film over the aperture and attach it to the cardboard carefully with cellophane tape, being sure to tape only that part of the film overlapping the edge of the opening. Have the axes of both films in the same direction (Fig. 5).

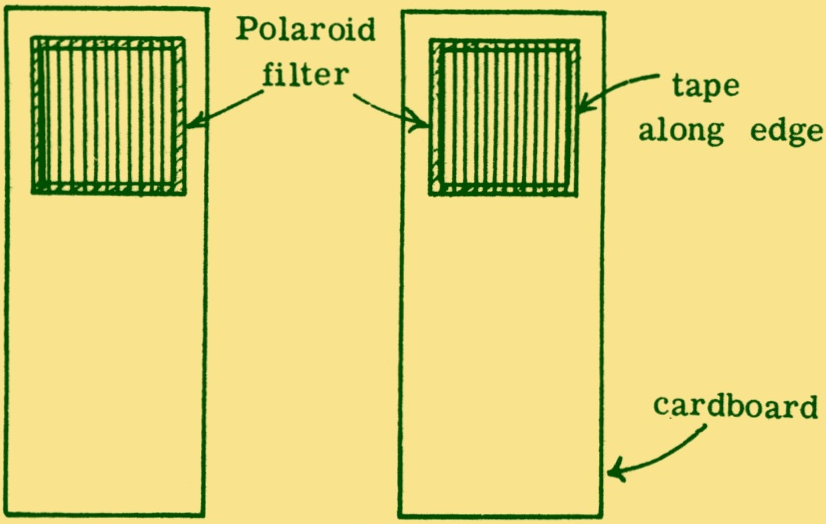


Fig. 5

POLARIZATION BY REFLECTION

Experiment 6. Hold a printed sheet of glossy white paper flat in the bright sunlight or in artificial light. A page from a "slick" magazine is excellent for this experiment.

Look downward on the page obliquely or at a slant, adjusting your position until you find an angle at which a bright glare reaches your eyes from the surface. Look into the glare and try to read the printed words. Can you? Note that where the glare is the brightest, it is impossible to read the words.

When light is reflected obliquely from a sheet of glossy paper, a polished desk top, tarred or wet road, or just about any other smooth nonmetallic surface, almost all of its rays are reflected in a single plane and consist mainly of waves vibrating horizon-

tally. The light therefore is polarized (Fig. 6).

You have probably observed this phenomenon as you looked obliquely at the surface of water of an ocean or pool. Some of the light striking the surface of a body of water is also refracted downward into the water. This light is also polarized.

Experiment 7. Hold one of your linear polarizing filters between your eye and the glaring surface of the horizontal paper. Can you now read the words?

Turn the filter as you would a wheel. Does the amount of glare change as you rotate the polarizer?

Is there some position (azimuth) of the polarizer which stops the glare almost entirely? When you find this azimuth, mark a point with a pencil above the filter on the cardboard holder. Make another dot directly opposite it below the filter. An imaginary line drawn from one point to

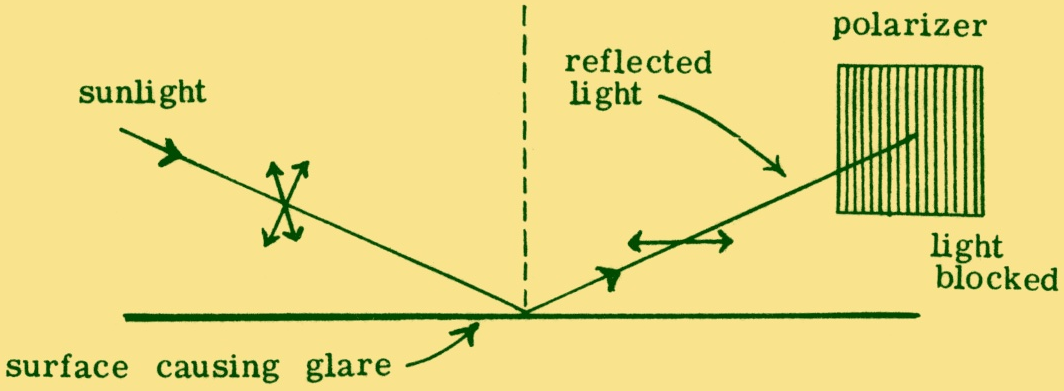


Fig. 6

the other is called the transmission axis, or the vibration direction of the polarizer. The line you have located is parallel to the direction in which the plastic of the polarizer was originally stretched, or to the alignment of the molecules.

Now turn the polarizer so that the line or transmission axis of your Polaroid is horizontal and verify that the transmission (and glare) is greatest in that position.

Find the axis for the second polarizer also.

This experiment illustrates how a polarizer affects glare. Oriented one way, the polarizer's countless parallel molecules let the glare from horizontal surfaces pass through readily, but turned through 90°, they stop the polarized beam completely. Only the unpolarized light is allowed to pass through.

The anti-glare function of the polarizer should immediately suggest its many uses for this purpose. The ordinary "dark sunglasses" used to protect eyes from harmful effects of the sun cut down the brightness of the light, but do not reduce the polarized glare-producing light rays as a polarizing lens does. Most military sunglasses, as well as many optical instruments like telescopes and range finders utilize polarizing filters.

Most of us are not aware of the fact that much of the light we use to see by is polarized. Light rays from the sun reflected from various surfaces move in particular planes as beams of polarized light, brightening up other surfaces and the surroundings.

Experiment 8. Look around you and observe the many brightly lighted surfaces. View them through one of your Polaroid films turning the filter slowly and determine which are reflecting polarized light. If you cannot block out the glare completely with the polarizer, you will know that the light is not polarized.

POLARIZATION BY SCATTERING

Experiment 9. Face away from the sun and look at a clear blue sky without the polarizer. Now look at the sky through one of your Polaroid films, turning it fairly quickly as you do so. (If you do not turn the polarizer rather rapidly, the change in intensity may be obscured by the adaptation of your eyes.) Do you find that the light from the sky is polarized also? Note that the intensity of the light transmitted through the polarizer changes as you turn it.

The extent of polarization is greatest when the sky is observed at right angles

to the direction of the light rays from the sun. Test this. NEVER LOOK DIRECTLY AT THE SUN EVEN THROUGH THE POLAROID FILM.

This is an example of polarization by scattering. The light from the sun is scattered by the molecules composing the atmosphere and the dust particles in the air. The light polarized by scattering in the air vibrates in a plane perpendicular to the sun-earth direction, the direction of the original ray (Fig. 7). Check this with the axis you have marked on your polarizers.

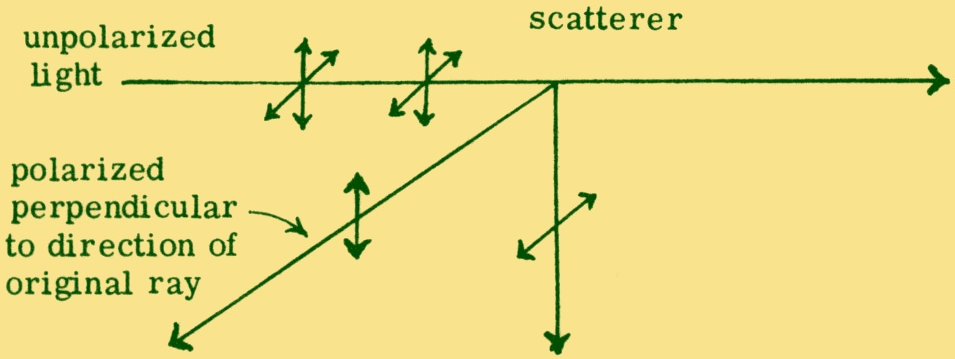


Fig. 7

Experiment 10. Make a very pale, thin solution of milk in water, using just one small drop of milk to a large glass of water. In a darkened room, shine a flashlight beam through the glass from one side and observe the light beam from above. Look through a Polaroid filter at the light scattered by the milk particles. Is

it polarized? At what angle of viewing do you find the maximum polarization?

As with the light from the sky, the maximum extent of polarization of the light scattered by the milk solution is found at right angles to the beam of light.

Experiment 11. On a sunny day when there are a few clouds in the sky, look at the sky at right angles to the sun. How sharply can you make out details of the clouds?

Now place the polarizer between your eyes and the sky. Turn the polarizer slowly and notice that as the brightness of the blue sky is reduced, the clouds stand out more and more boldly. You have increased the contrast between sky and clouds.

The light of the blue sky is polarized, but light from the clouds is not. The clouds are composed of small droplets of water each of which reflects light in a different direction. Therefore, when you look through the polarizer and orient the polarizer properly, you shut out a large percentage of the polarized light from the sky. The clouds stand out vividly because the intensity of the blue sky is reduced.

This principle is often employed in photography. To make clouds stand out in a picture or to reduce any other source of glare in a photograph, a polarizing filter

is placed in front of the camera lens.

CIRCULARLY POLARIZED LIGHT

Experiment 12. Place one of the polarizing filters on a small mirror. Note that you can see the reflection of your eye through the Polaroid film. Slip your quarter-wave retardation film between the Polaroid film and the mirror with the edges of both films lined up with each other. Can you still see your reflection?

Now turn the quarter-wave film so that its edges are at a 45° angle to the Polaroid film. Look again at the mirror. You will see that your reflection is completely blacked out.

By adding the quarter-wave retardation film you have converted the linearly polarized light produced by the polarizing film into circularly polarized light. The vibrations of the linearly polarized light emerging from the Polaroid film have been given a "twist" by the quarter-wave retardation film to produce circularly polarized light. The vibrations are no longer arranged in a single plane. Instead, they behave as if they now form a helix, like the thread on a bolt.

The "twist" is created because the quarter-wave retardation film divides the linearly polarized beam into two sets of vibra-

tions of equal intensity, but slightly out of step. One is retarded. The thickness of the retardation film is carefully selected so that the retarded beam is one-quarter of a wavelength behind the other beam, and this results in the "twist."

Light passes through the quarter-wave film twice. First when it is twisted clockwise as it travels toward the mirror and again when it bounces back from the reflecting surface spiraling counterclockwise. After passing through the quarter-wave film a second time, the light waves have

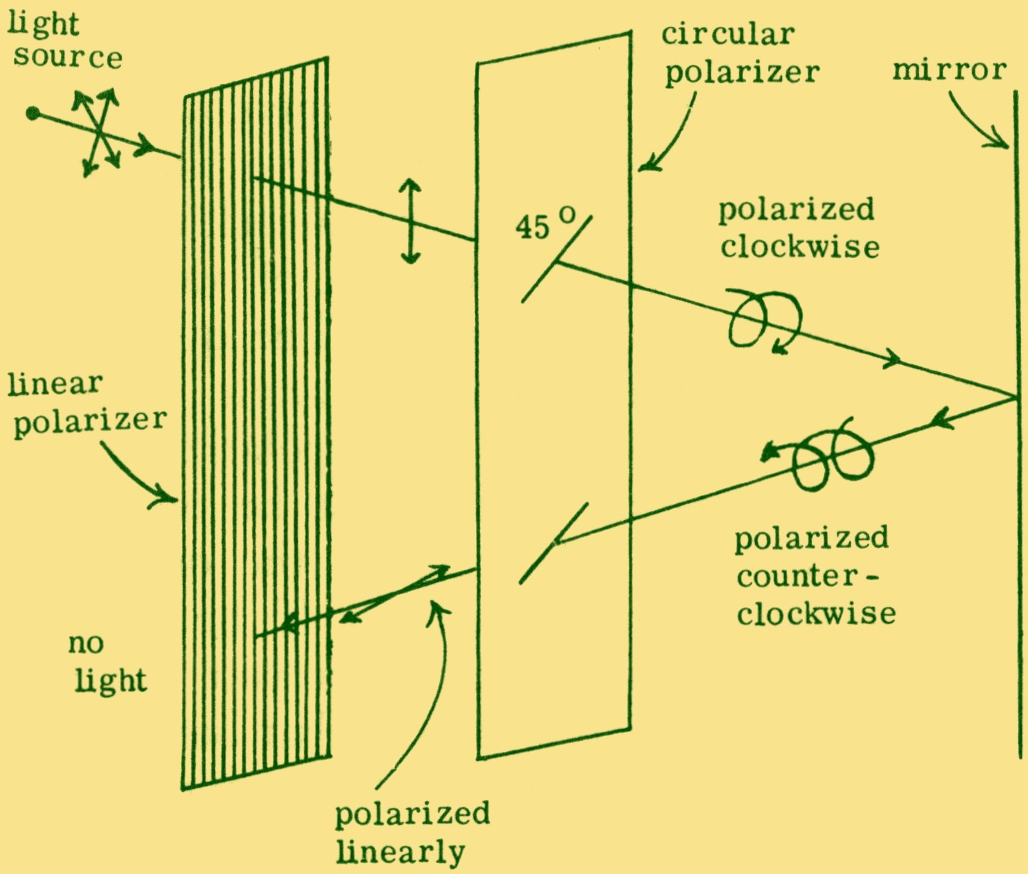


Fig. 8

been rotated 90° and are at right angles to the linear polarizer. Therefore, the reflected light is blocked (Fig. 8).

The retardation film itself has an axis. When its axis is placed at 45° to the right of the axis of the polarizer, it produces right-handed circularly polarized light. If it is placed at 45° to the left of the polarizer axis it produces left-handed circularly polarized light.

The usefulness of circular polarizers stems from the fact that a right-handed beam cannot pass through a left-handed circular polarizer, no matter how the polarizer may be rotated.

Experiment 13. You can demonstrate this by cutting the quarter-wave film in half and attaching one piece to each of the polarizing filters. A thin film of vaseline will hold the filters together. The quarter-wave films must be at a 45° angle to the transmission axis of the linear polarizers.

The retardation films must be on the inside, and the polarizers on the outside as you look through the films. If the circular polarizers stay clear when you rotate one over the other, it means that both are right-handed or both are left-handed, so change the orientation of the retardation film on one of the Polaroid films.

Further, a right-handed beam, when re-

flected from a non-depolarizing surface, becomes a left-handed beam, and therefore cannot pass through the same filter that originally polarized it, as you have seen in your experiment with the mirror.

By attaching the quarter-wave film to the polarizing filter, you made a circular polarizer. Circularly polarizing filters are widely used to eliminate reflections from radar screens, oscilloscopes and other instruments.

BIREFRINGENCE

Experiment 14. Place your two polarizing filters opposite each other about one inch apart with their axes parallel. Obtain a thin sheet of glass and place it between the two polarizers. Look through the combination while slowly revolving one of the polarizers. Do you notice any unusual effects?

No, because a thin sheet of glass usually does not affect polarized light. Light vibrating in any direction will pass through ordinary glass. Therefore, as one polarizer is turned, the intervals of light and blackout alternate as they would if the glass were not present.

Experiment 15. Now place your sheet of cellophane between the two filters and rotate one of the Polaroid films slowly.

What do you see? Does the color change as one filter is turned?

Experiment 16. Cut off a 1½-inch piece from the 3-inch end of the sheet and crumple it up tightly. Open up the crumpled cellophane gently, leaving in the wrinkles. Observe the cellophane between the two polarizers, rotating one of them. Do you see more than one color? Do the colors change as you rotate the polarizer?

The beautiful sequence of colors observed in these experiments illustrates the phenomenon of birefringence, the ability of a material to change the kind of vibration of polarized light passing through it. The cellophane behaves somewhat like the quarter-wave film, converting some wavelengths of plane polarized light (colors) into circularly polarized light. Some of the wavelengths are left plane polarized, but most of the wavelengths are transmitted as a mixture of plane and circularly polarized light.

A ray of polarized light, which would ordinarily be blocked off by a second polarizer, therefore, may be "reprieved" if it is retarded slightly, so that some light may pass through the second polarizer. Depending on the amount of alteration by a birefringent material, a ray may pass through the second unit of a pair of

crossed polarizers with small, moderate or full intensity.

But why are colors seen? Because birefringent materials convert or retard light of different wavelengths (different colors) in different amounts. For example, a single cellophane layer may produce enough retardation to make blue light into circularly polarized light part of the way through the material and convert it back to linearly polarized light with a new axis on emerging. Red light may come through with complete circular polarization. This would mean that the blue light would pass through the sandwich to reach the eye, while red light would be partly blocked.

Different wavelengths of light are retarded by differing amounts by the cellophane. A wavelength of light, which is retarded just the right amount so that its new plane of linearly polarized vibration is parallel to the axis of the second polarizer, will be transmitted in its color. If a wavelength is retarded so that its plane of vibration is at right angles to the plane of transmission of the polarizer, it will be blocked and its color will not show. Those wavelengths which are made into circularly polarized light will be only partly transmitted by the second linear polarizer.

Experiment 17. Take the larger piece

of cellophane and fold it. Place it between the polarizers and note the colors as you turn one of the filters. Now fold it again so that you have four layers. Observe the colors. Have they changed? Repeat the folding and note that each time the number of layers changes, the combination of colors changes. Now keep the polarizers stationary and turn the cellophane. Do you see other colors?

By increasing the number of layers of cellophane more retardation occurs and a color that could not pass through the sandwich before will now pass through, and likewise, colors that could pass through will now be blocked.

Hold the polarizers together so that their axes are crossed and no light can pass through. Now place the cellophane folded over once or twice between them. As you turn the cellophane you will see that where no light had passed through before, a color will appear.

Experiment 18. Now cut two strips in the same direction from your cellophane about ¼ x 2 inches long. Place the strips diagonally across one of the polarizers to form an "X" and secure them to the cardboard backing of one of your polarizers with tape or a bit of glue. Hold the second polarizer in front of this polarizer, being

Fig. 9

sure the cellophane X is between the two. Do the arms of the X appear blue? What is the color of the center of the X where the two arms cross?

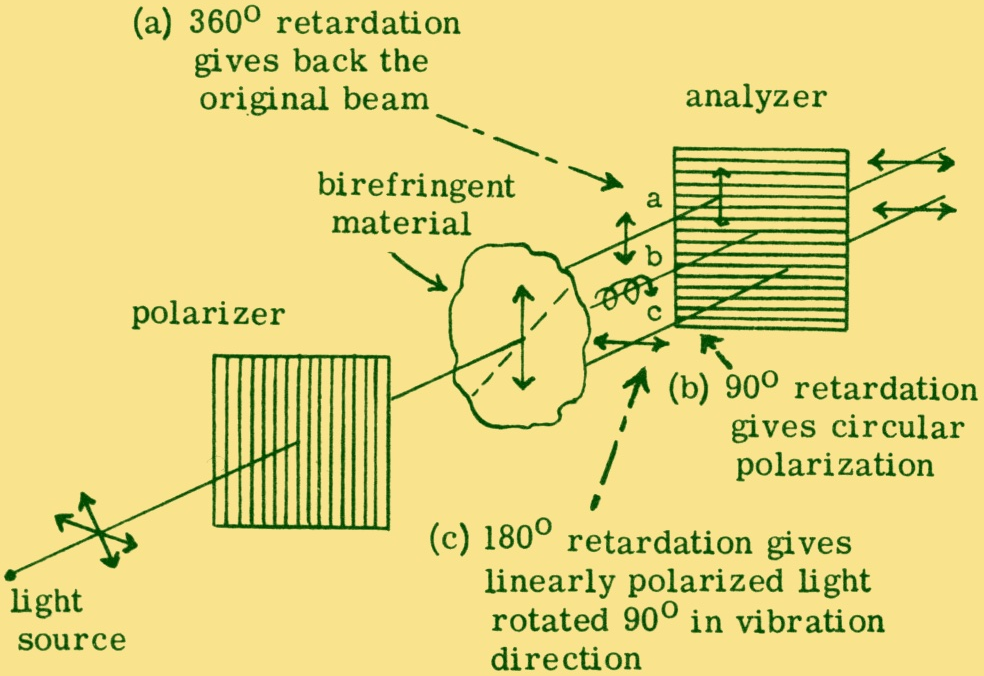
Make a quarter turn of the filter in front. What happens? The arms now appear yellow, the complement of blue, and the center blue.

Experiment 19. From the remaining cellophane cut six pieces of the same width, about ⅜ inches wide. Make the first one inch long and each of the others 1/16 of an inch shorter than the preceding one. Place one upon the other in order of decreasing length to form a series of "steps." The steps will increase in thickness of cellophane from one to six layers (Fig. 9).

Secure the six-layer end with cellophane tape, being sure not to extend the tape inward for more than about one-eighth inch. Place the step arrangement between your two polarizers, and note the array of colors. Give the polarizer in front a quarter turn. Do all the colors change? Are the new colors complements of the previous ones?

Experiment 20. Many natural crystals

are birefringent and this gives scientists a means of examining the internal, microscopic structure of crystals by means of polarized light. A simple device widely used for this purpose, called a polariscope, consists of two polarizers, the polarizer and analyzer, with a space between for the samples to be tested (Fig. 10). The crystals placed in the polariscope yield varying color patterns according to their structures, just as the folded cellophane revealed different color patterns in crossed polarizers.



Showing the effect of varying thicknesses of birefringent material on one wavelength.
(a) No transmission.
(b) Partial transmission.
(c) Full transmission.

Fig. 10

The white, fluffy harmless benzoic acid in this unit is a birefringent, or doubly refractive, crystal.

Obtain a piece of clean thin glass, such as a microscope slide, and another piece of very thin glass ready to use as a cover glass.

Place a small amount of benzoic acid, a lump smaller than the size of a match head, on one end of the slide. Spread it out into a thin layer about ½-inch square with a toothpick or tweezers, NOT YOUR FINGERS.

With a small candle flame heat the crystals by moving the glass continually above the flame. Do this at arm's length AT THE SINK WHERE WATER IS READILY AVAILABLE. Avoid breathing in any fumes produced by heating.

The benzoic acid crystals will soon melt. When melted, remove the flame and carefully, but quickly, place the thin cover glass over the melted crystals which should spread out thinly and evenly under the glass. Almost immediately the benzoic acid will recrystallize.

Now hold your prepared slide of benzoic acid crystals between the two polarizers. Turn one of the polarizers to see the colors change. Use a hand lens, if necessary, to observe the various colors.

In this experiment it is important to

obtain a very thin layer of crystals on the slide for successful demonstration. You may have to experiment several times before making a good specimen.

Experiment 21. Mica too is a doubly refractive substance. Examine your mica. It is made up of many ultra-thin layers.

Sandwich your mica between the polarizers. Observe the array of colors as you turn the polarizer. Turn the mica to a different angle and look through the polarizer again as you rotate it, noting the new colors that appear.

Tear the mica obliquely so that the ends expose several layers. Notice the different colors produced by the various thicknesses.

Experiment 22. Cross the Polaroid filters at right angles and turn the mica slowly between them. Note that in one complete turn of 360°, the light coming through the film is blocked off completely four times. When the optic axis of the mica is either parallel or perpendicular to the vibration plane of the light rays, only one component of the split beam passes through the mica. This in turn is blocked by the second polarizer and no color or light is observed.

Experiment 23. Place the mica between the polarizers again. Rotate the polarizer one quarter turn or 90° so that

the axes are at right angles. Do the colors change to their complements?

As in Experiment 18, if a polarizer transmits only vertical vibrations of polarized light and allows light of a certain wavelength to be transmitted, when it is turned 90° so that only horizontal vibrations are allowed to pass through, it will block that light. But if the light source is white light, then this rotation of 90° will change the overall color of the mica to its complementary color.

Experiment 24. Polarizers are used to examine materials for stress and strain.

Cut a piece about three inches square from the polyethylene bag in which your mica and filters were enclosed. Observe it between the filters. Does it behave like glass when one polarizer is rotated?

Now stretch the sheet by pulling it from opposite sides. This produces a strain in the material. Observe it between the two polarizers as one of the filters is rotated. Note the streaks of color here and there. The molecules in the stretched plastic have been pulled and twisted so that they line up differently from the molecules in the unstretched part of the polyethylene, indicating strain.

THINGS of science
POLARIZED LIGHT
Science Service Washington, D. C. 20036

Polarizers are used by industrial workers to check plastic models of structures, such as beams and bridges, for points of strain before the actual building starts. Polarizers are also employed to check glass for telescope mirrors for strain or weakness.

Polarizers have become one of the useful tools of mankind since its development. The subject is a fascinating one with many applications, including 3-D movies. If you wish to pursue the subject further, elementary physics textbooks will be very helpful. Also most books dealing with light usually devote a section to the subject.

Appreciation is expressed to the Polaroid Corporation, Cambridge, Mass., for contributing the Polaroid film and the quarter-wave retardation film; to the Asheville-Schoonmaker Mica Company, Newport News, Va., who provided the mica; and to the Merck Corporation, Manufacturing Chemists, Rahway, N. J., for donating the benzoic acid crystals.

We also extend our appreciation to Dr. Deane B. Judd, National Bureau of Standards, for reviewing this booklet.

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